The Effect of Radiative Cooling on the Scale-Dependence of Global Stellar and Gas Contents of Groups and Clusters of Galaxies

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ABSTRACT

It is widely believed that the global baryon content and mass-to-light ratio of groups and clusters of galaxies are a fair representative of the matter mix of the universe and therefore, can be used to reliably determine the cosmic mass density parameter $\Omega_{\rm M}$. However, this fundamental assumption is challenged by growing evidence from optical and X-ray observations that the average gas mass fraction and mass-to-light ratio increase mildly with scale from poor groups to rich clusters. Although a number of time-consuming hydrodynamical simulations combined with semi-analytic approaches have been carried out, which permit a sophisticated treatment of some complicated processes in the formation and evolution of cosmic structures, the essential physics behind the phenomenon still remains a subject of intense debate. In this *Letter*, using a simple analytic model, we show that radiative cooling of the hot intragroup/intracluster gas may allow one to reproduce the observed scale-dependence of the global stellar and gas mass fractions and mass-to-light ratio of groups and clusters, provided that about half of the cooled gas is converted into stars. Together with the recent success in the recovery of the entropy excess and the steepening of the X-ray luminosity-temperature relations detected in groups and clusters, radiative cooling provides a simple, unified scheme for the evolution of hot gas and the formation of stars in the largest virialized systems of the universe.

Subject headings: cosmology: theory — galaxies: clusters: general – galaxies: formation — intergalactic medium

Groups and clusters serve as a reservoir of baryons in the present universe, which exist in the form of hot plasma with temperature close to the virial temperature (10^6-10^8 K) of the underlying gravitational potential wells as a result of gravitationally-driven shocks and adiabatic compression (Cen & Ostriker 2000). The hot intragroup/intracluster gas would continuously lose energy due to thermal bremsstrahlung and line emissions. The decrease in X-ray temperature T is completely governed by the conservation of energy, $(3/2)nkT = \epsilon(n,T)t_{\rm cool}$, where n is the total gas number density, and ϵ is the emissivity. This defines the so-called cooling time $t_{\rm cool}$ and radius $r_{\rm cool}$ within which gas can cool out of the hot phase. If the cooling time is set to equal the age of groups/clusters, or approximately the age of the universe, t_0,

we will be able to estimate the maximum cooling radii of the systems by the present time, $r^{\rm m}_{\rm cool}$, and the corresponding critical gas density, $n(r^{\rm m}_{\rm cool})$. Since the pioneering work of White & Frenk (1991), such a simple model for radiative cooling has been well incorporated in the study of formation and evolution of galaxies (e.g. Kauffmann, White & Guiderdoni 1993; Kauffmann et al. 1999; Benson et al. 2000; Wu, Fabian & Nulsen 2000; 2001; Somerville et al. 2001; Balogh et al. 2001; Yoshida et al. 2002; etc.).

We assume that in the absence of cooling the gas has the same distribution as the dark matter in groups and clusters. We adopt the universal density profile $\rho_{\rm NFW}(r) \propto 1/[cr(1+cr)^2]$ suggested by numerical simulations for the dark halos of groups/clusters (Navarro, Frenk & White 1997) and specify the concentration parameter c by $c = 10(M/2.1\times10^{13}M_{\odot})^{-0.14}$ for a given halo of mass M (Bullock et al. 2001). The number density of the hot gas thus follows $n(r) = (f_{\rm b}/\mu m_{\rm p})\rho_{\rm NFW}(r)$, where $f_{\rm b}$ is the universal baryon fraction, and $\mu = 0.59$ is the mean molecular weight. We assign an X-ray temperature to each halo in terms of cosmic virial theorem, $M \propto T^{3/2}$ (Bryan & Norman 1998).

The gas within the maximum cooling radius $r^{\rm m}_{\rm cool}$ is assumed to convert into stellar objects (Pearce et al. 1999; Bryan 2000). Note that this latter component should also include other possible cooled materials (e.g. neutral and molecular gas) which may form out of cooling process. The cooled gas mass within $r^{\rm m}_{\rm cool}$ can be obtained by integrating the gas profile $n(r)$ over volume out to $r^{\rm m}_{\rm cool}$. Actually, such a simple exercise gives rather a robust estimate of the total stellar mass of a system, $M_{\rm star}$, as has been shown recently by Yoshida et al. (2002). The gas outside $r^{\rm m}_{\rm cool}$ may also give some contribution to $M_{\rm star}$. This happens because the central region can be refilled with the hot gas distributed originally at large radii due to the lack of pressure support once the gas within $r^{\rm m}_{\rm cool}$ cooled out of the hot phase. Here we use a less vigorous method to estimate the amount of this secondary cooled component due to successive cooling. We first work out the newly established gas distribution by combining the conservation of entropy and the equation of hydrostatic equilibrium (Bryan 2000; Voit & Bryan 2001; Wu & Xue 2002). We then play the same game as the above by setting the age of the universe to equal the cooling time, which defines the secondary cooing radius and thus yields the total mass of corresponding cooled material. Numerical computation shows that the contribution of this inward flow to the total stellar mass is less than 20% in groups and clusters. Finally, we obtain the stellar and gas mass fractions from $f_{\rm star} = M_{\rm star}/M$ and $f_{\rm gas} = f_{\rm b} - f_{\rm star}$, respectively. Because the hot gas cools relatively faster in groups than in clusters due to the difference in their density contrasts and/or temperatures, poor groups experienced higher efficiency of star formation than rich clusters did. Therefore, a(n) decrease (increase) of stellar (gas) mass fraction from groups to clusters is expected to occur naturally (Pearce et al. 1999). A long standing question is: Can the expected scale-dependence of $f_{\rm star}$ and $f_{\rm gas}$ as a result of radiative cooling be quantitatively reconciled with observations ?

We take a flat, cosmological constant dominated cosmological model to proceed our numerical calculation: $\Omega_{\rm M} = 0.3$ and $\Omega_{\Lambda} = 0.7$, in which the baryon density is $\Omega_{\rm b} = 0.047$ for a Hubble constant of $H_0 = 65$ km s^{-1} Mpc^{-1}. The present age of the universe is correspondingly $t_0 = 14.5$ Gyr. We employ an optically thin and isothermal plasma emission model with a primordial mixture of 77% hydrogen and 23% helium and a metallicity of 30% solar (Raymond & Smith 1977). In Figure 1 we compare our predicted stellar and gas mass fractions as a function of X-ray temperature T with three optical and X-ray observations of 33 groups and clusters (Mulchaey et al. 1996; Cirimele, Nesci & Trevese 1997; Hwang et al. 1999). These samples were used as an input in the galaxy formation-regulated gas evolution model aimed at the explanation of the observed entropy floor in the central cores and X-ray luminosity distribution of groups and clusters (Bryan 2000; Wu & Xue 2002). Because the theoretical predictions of $f_{\rm star}$ and $f_{\rm gas}$ depend critically on the truncated radii of groups and clusters, we demonstrate the results for two choices of

overdensity parameter, $\Delta = 200$ and 2500, which cover roughly the observational range according to the calibration of Evrard, Metzler & Navarro (1996). While there is essentially a good agreement between the theoretical predictions and the observations, the observed data within different radii which increase roughly from groups (larger Δ) to rich clusters (smaller Δ) may also introduce a systematic bias giving rise to the similar scale-dependence. In order to eliminate this concern, we turn to the sample of Roussel, Sadat & Blanchard (2000) who derived the stellar and gas mass fractions of 33 groups and clusters out to the virial radii. Of course, their result should also be used with caution because the evaluation of the total stellar and gas mass fractions requires a substantial extrapolation of the observational data to virial radii especially for groups and poor clusters. Recall that the β parameters in the X-ray surface brightness profiles of groups and poor clusters revealed by current observations are often smaller than ~ 0.6, yielding a monotonically increasing gas mass fraction with radius (Wu & Xue 2000). This may lead to a significant overestimate of the total gas mass fractions of groups and poor clusters. The observed data of Roussel et al. (2000) are illustrated in Figure 2, together with our predictions in terms of radiative cooling. Although Roussel et al. (2000) didn't found any strong evidence for a positive correlation between gas mass fraction and temperature, their data, nevertheless, are still consistent with the mild increase of $f_{\rm gas}$ with T expected from the cooling model. However, the stellar mass fractions in most of the groups and clusters are smaller than the theoretical prediction by a factor of ~ 2. This discrepancy indicates that a considerably large fraction of the cooling gas in groups and clusters may not be converted into stellar objects. Instead, the cooling gas may end up in other forms such as cold clouds. Alternatively, the discrepancy seems to be more significant on group scales than on cluster scales. Namely, the theoretically predicted scale-dependence of $f_{\rm star}$ is slightly stronger than the observation. Yet, the observations are at present uncertain, so that such a claim may still be premature.

It follows immediately that the dependence of the stellar mass fraction of groups and clusters on X-ray temperature would result in a variation of mass-to-light ratio from groups to clusters. This happens because the mass-to-light ratio can be formally written as $M/L = (M/M_{\rm star})(M_{\rm star}/L) = \Upsilon/f_{\rm star}$, where $\Upsilon \equiv M_{\rm star}/L$ measures the efficiency with which groups and clusters transform cooled material into light. Once this free parameter is specified, we will be able to predict how M/L varies with M or T.

Bahcall & Comerford (2002) have compiled a sample of 21 systems whose X-ray temperatures and mass-to-light ratios are reliably determined. Over the temperature range from groups ($kT = 0.73$ keV) to rich clusters ($kT = 12.3$ keV), they have found that M/L_V, which are corrected to redshift $z = 0$, show an increasing tendency toward high temperature clusters. In Figure 3 we illustrate their observed M/L_V versus kT, together with our theoretical predictions for $\Upsilon = 7.5\Upsilon_\odot$. It turns out that the two results are reasonably consistent with each other. The slightly large value of $\Upsilon = 7.5\Upsilon_\odot$ as compared with that ($\approx 5\Upsilon_\odot$) of early-type galaxies (Fukugita, Hogan & Peebles 1997) may arise from the fact that our total stellar mass $M_{\rm star}$ from cooling model has also included other cooled components (e.g. cold clouds). However, there exist two biases which may invalidate our comparison: The observed data were taken within different radii of groups and clusters, which may lead to an increasing M/L with T if the X-ray measurements had a bias toward the selection of central X-ray luminous regions for low-mass systems (groups) but more extended regions for rich clusters. Another bias factor arises from the fact that Υ itself may have a positive correlation with M or T (Balogh et al. 2001), in the sense that groups contain mainly spirals ($M/L_B \approx 1.5\Upsilon_\odot$) while rich clusters are dominated by ellipticals ($M/L_B \approx 6.5\Upsilon_\odot$) (Fukugita et al. 1997).

Next, we turn to the hitherto largest sample of M/L_B for groups and clusters compiled recently by Girardi et al. (2002). We restrict ourselves to the massive systems with $M \geq 10^{13}M_\odot$ to ensure that the

dominant X-ray emission is produced by 'primordial' gas rather than stellar winds, supernova remnants or star binaries. This reduces to a subsample of 213 systems (see Figure 4). Meanwhile, both M and M/L_B of all the systems have been computed to their virial radii, which eliminates at least one of the concerns addressed above. Yet, the data set has its own problem: The two variables, M/L_B and M, are not independent of each other. This arises from the fact that in their sample the uncertainty in M is larger than that in L_B, and the error ellipses introduce an intrinsic, positive correlation between the two quantities. In Figure 4 we demonstrate our predicted M/L_B versus M assuming $\Upsilon = 8.5\Upsilon_\odot$. The adoption of $\Upsilon = 8.5\Upsilon_\odot$ in the B band required to match the observed M/L distribution is compatible with $\Upsilon = 7.5\Upsilon_\odot$ in the V band used in Figure 3, if we make use of the synthetic model by Charlot et al. (1996) to calculate the $B-V$ color for a galaxy age of ~ 12 Gyr. The larger Υ parameter relative to the mean value of $\Upsilon \approx 4.5\Upsilon_\odot$ for a typical cluster (Balogh et al. 2001) implies that about half of the cooled gas deposited from cooling flows may condense into other form of cold materials in the central regions of groups and clusters. This conclusion is consistent with the existence of the discrepancy between the predicted and observed cooled gas components shown in Figure 2.

We can also evaluate the mass deposition rate $\dot{M}_{\rm cool}$ within cooling radius and its cosmic evolution: $\dot{M}_{\rm cool} = 4\pi(f_b/\mu m_{\rm p})\rho_{\rm NFW}(r_{\rm cool})r_{\rm cool}^2\dot{r}_{\rm cool}$, where $\dot{r}_{\rm cool}$ is determined by combining the conservation of energy with the self-similar model (NFW) for gas. It appears that if about half of the cooling gas is converted into stars, our estimated $\dot{M}_{\rm star}$ at present epoch varies from 10 $M_\odot$/yr for groups of $M = 10^{13}$ $M_\odot$ to 500 $M_\odot$/yr for clusters of $M = 10^{15}$ $M_\odot$. This indicates substantial and on-going star formation in today's rich clusters. The detection of anomalously blue colors in the central regions of clusters (Allen 1995) does give support to a high rate of recent star formation, though a quantitative comparison with observations is hampered by large uncertainty in the current derived star formation rate in clusters. Recent Chandra observations of several rich clusters have revealed that the integrated mass deposition rates are about $100 - 500$ $M_\odot$/yr within the cooling radii (~ 100 kpc) and drop to ~ 10 $M_\odot$/yr in the very central regions (~ 10 kpc) (Allen et al. 2001; Allen, Ettori & Fabian 2001; Schmidt, Allen & Fabian 2001; Ettori et al. 2002; etc.). Alternatively, our predicted stellar mass fraction and star formation rate show no significant change between nearby and distant groups/clusters out to redshift $z \approx 1$ if they have the same mass, implying an early formation of stars in groups and clusters and little cosmic evolution of their stellar mass fractions and mass-to-light ratios within $z \approx 1$. Note that the concentration parameter c of a distant dark halo at redshift z decreases by approximately a factor of $(1+z)$ as compared with that of a nearby halo with identical mass (Navarro et al. 1997; Bullock et al. 2001). Namely, while the young age of high-redshift clusters is unfavorable for the accumulation of cooled material, the dense matter environment of the clusters gives rise to a relatively short cooling time. The combined effect accounts for the lack of significant cosmic evolution of $f_{\rm star}$, $f_{\rm gas}$ and M/L since $z \approx 1$.

We have so far concentrated on the global properties of groups and clusters as a consequence of radiative cooing. In fact, the regulated gas distribution in groups and clusters produced by cooling or star formation resembles the conventional β model in shape (Wu & Xue 2002). In particular, the scale-dependence of radiative cooling or star formation process explains naturally the entropy excess and the steepening of the X-ray luminosity-temperature relations in groups and clusters (Bryan 2000; Pearce et al. 2000; Muanwong et al. 2000; Voit & Bryan 2001; Wu & Xue 2002). In a word, radiative cooling of the hot intragroup/intracluster gas, which is based on the well-motivated physical process, may allow us to resolve all the puzzles seen in current X-ray observations of groups and clusters, and energy feedback from star formation comes into effect only in the less massive systems of $M < 10^{13}$ $M_\odot$.

Apparently, the present simple model has its own problems that need to be resolved in the future.

First, the cosmic evolution of groups and clusters has not been included, which is relevant to the well-known overcooling crisis if massive dark halos like groups and clusters form by gravitational aggregation of individual low-mass galaxies. Our analytic cooling model is only applicable to the case when most of the hot gas had already assembled in groups and clusters. In other words, we have attempted to address the question of how much the hot gas heated by gravitational shocks and adiabatic compression in groups and clusters has cooled out of the hot phase by the present epoch. Second, our model without the inclusion of energy feedback from star formation becomes invalid for low-mass systems of $M < 10^{13}\ M_{\odot}$, because the hot gas can be expelled by supernova explosion from the shallow gravitational potentials of these systems. In effect, our simple model predicts that radiative cooling alone may have consumed most of the hot gas in galaxies with masses below $10^{12}\ M_{\odot}$. This is at odds with the recent estimate of the global fraction of baryons which have cooled by now (Balogh et al. 2001). In addition, the cooling model seems to yield somewhat a stronger scale-dependence of cooled gas component than both observations (Figure 2) and hydrodynamical simulations (Figure 4), regardless of the discrepancy of a factor of ~ 2 in amplitude. This could also be attributed to the influence of star formation. Indeed, energy feedback can heat the intragroup/intracluster medium, which is equivalent to suppressing the cooling efficiency. The fact that the effect is more significant in groups than in clusters may suppress moderately the scale-dependence of the cooled gas content predicted by radiative cooling. Third, the main reason behind radiative cooling for the scale-dependence of stellar and gas contents of groups and clusters remains unclear. Recall that the present investigation is based solely on the conservation of energy, $(3/2)nkT = \epsilon(n,T)t_{\rm cool}$. Either higher gas density (n), or lower temperature (T), or less thermal energy $[(3/2)nkT]$ in low-mass systems (e.g. poor clusters and groups) should be able to account for the scale-dependence of stellar and gas contents from groups to clusters. Future work will thus be needed to clarify the issue.

We gratefully acknowledge the constructive suggestions by an anonymous referee. This work was supported by the National Science Foundation of China, the Ministry of Science and Technology of China, under Grant No. NKBRSF G19990754, and the National Science Council of Taiwan, under Grant NSC91-2816-M001-0003-6.

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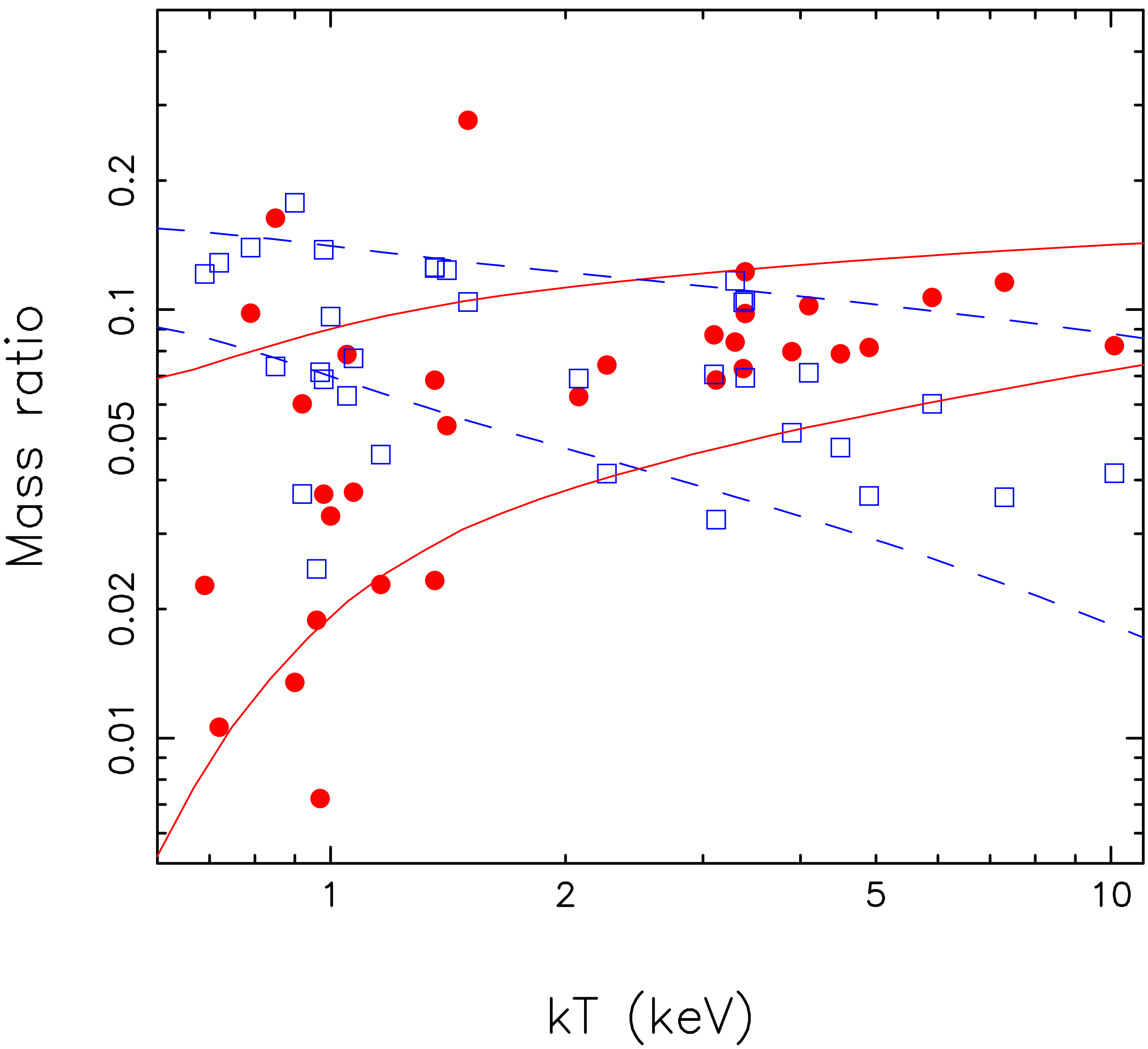
Fig. 1.— Gas mass fraction $f_{\rm gas}$ (solid lines) and stellar mass fraction $f_{\rm star}$ (dashed lines) as a function of temperature T predicted by radiative cooling are compared with the observed $f_{\rm gas}$ (filled circles) and $f_{\rm star}$ (open squares) of 33 groups and clusters (Mulchaey et al. 1996; Cirimele et al. 1997; Hwang et al. 1999). Since the observational results were obtained within different radii corresponding roughly to overdensity parameter ranging from 200 to 2500 in different groups and clusters, the theoretical predictions are plotted for two choices of overdensity parameter, $\Delta = 200$ and 2500, respectively.

Fig. 2.— Total gas mass fraction (solid line) and stellar mass fraction (dashed line) within virial radius predicted by radiative cooling are compared with the observed data of 33 groups and clusters by Roussel et al. (2000): filled circles - $f_{\rm gas}$, and open squares - $f_{\rm star}$. Dotted line represents the result when the cooled gas mass fraction is reduced by a factor of 2.

Fig. 3.— The dependence of mass-to-light ratio on X-ray temperature is shown for overdensity parameter $\Delta = 200$ (upper line) and $\Delta = 2500$ (lower line) assuming a cooled gas mass-to-light ratio of $\Upsilon = 7.5\Upsilon_{\odot}$ in the V band. The data points of 21 systems from Bahcall & Comerford (2002) measured within radii of typically 0.8 to 2.3 Mpc fall essentially within the theoretical predictions.

Fig. 4.— The dependence of mass-to-light ratio M/L on virial mass M. The observed data points of 213 groups and clusters (points) are taken from Girardi et al. (2002). Dashed line is our predicted M/L distribution for an overdensity of $\Delta = 200$ and $\Upsilon = 8.5\Upsilon_{\odot}$ in the B band. Solid lines represent the results obtained by numerical simulations (from top to bottom: Somerville et al. 2001; Benson et al. 2000; Kauffmann et al. 1999), in which the mean mass-to-light ratio of the universe has been assumed to be 878 $M_{\odot}/L_{\odot}$ for the data of Kauffmann et al. (1999).



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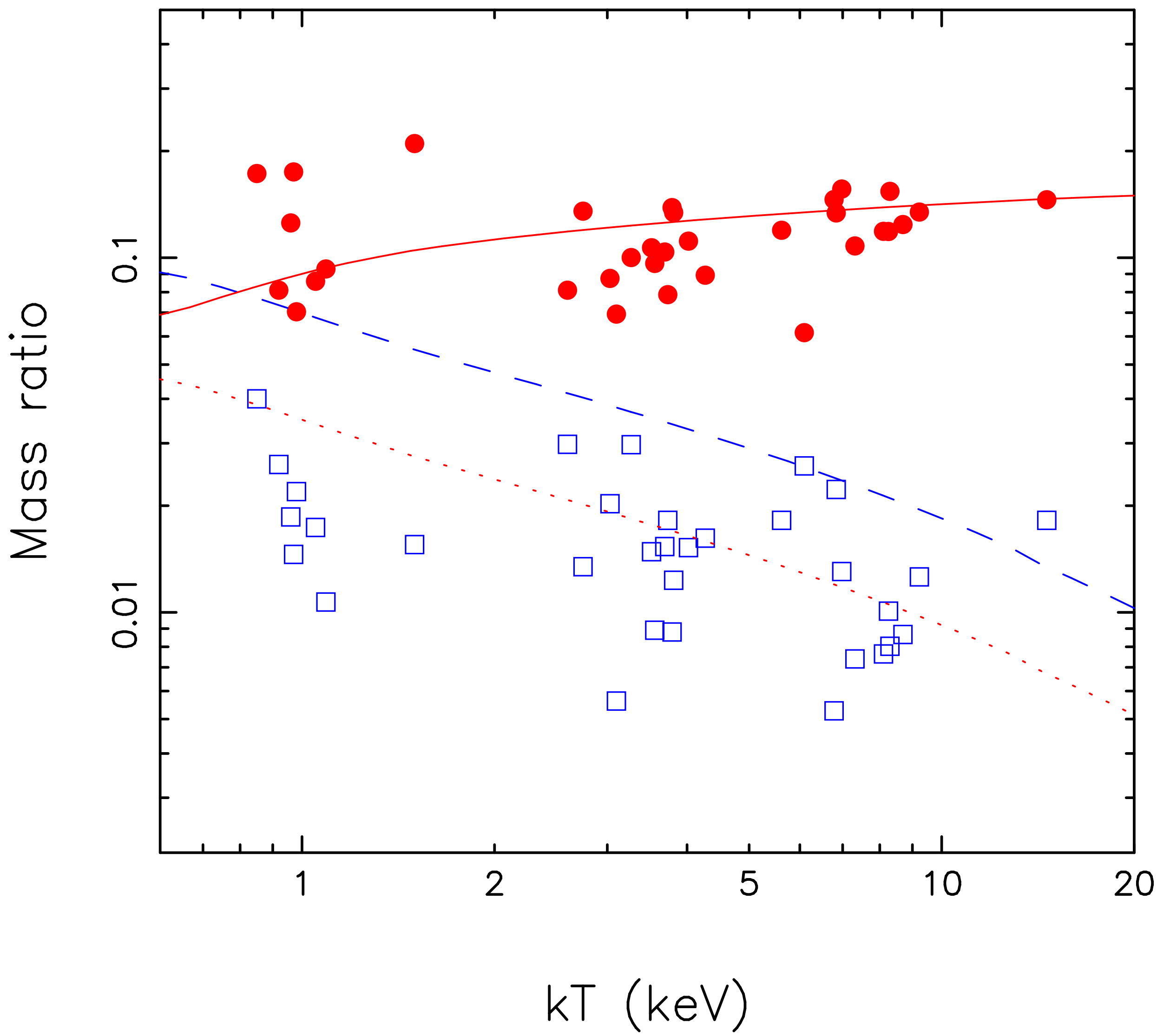

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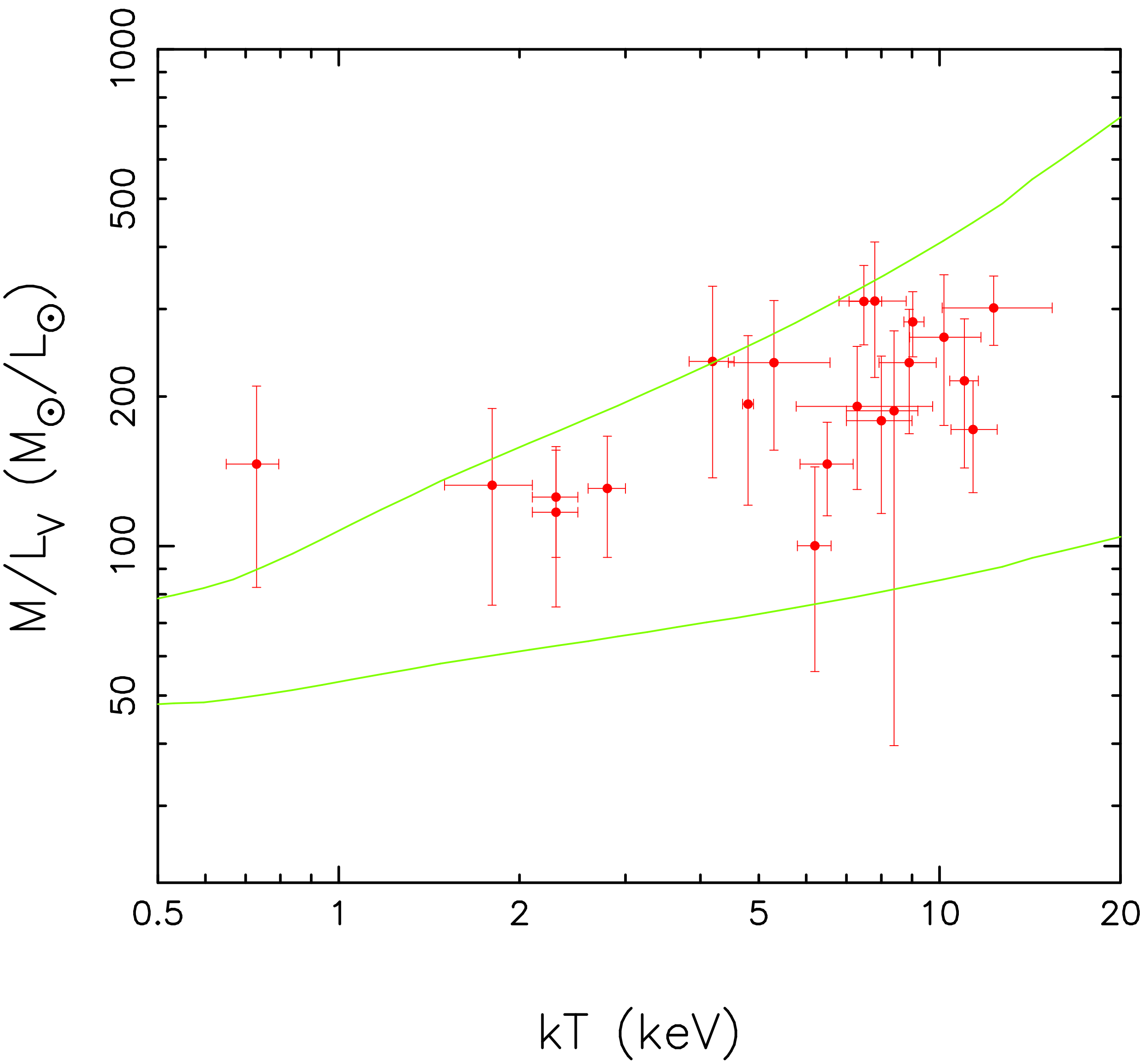
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M/L_V $(M_\odot/L_\odot)$
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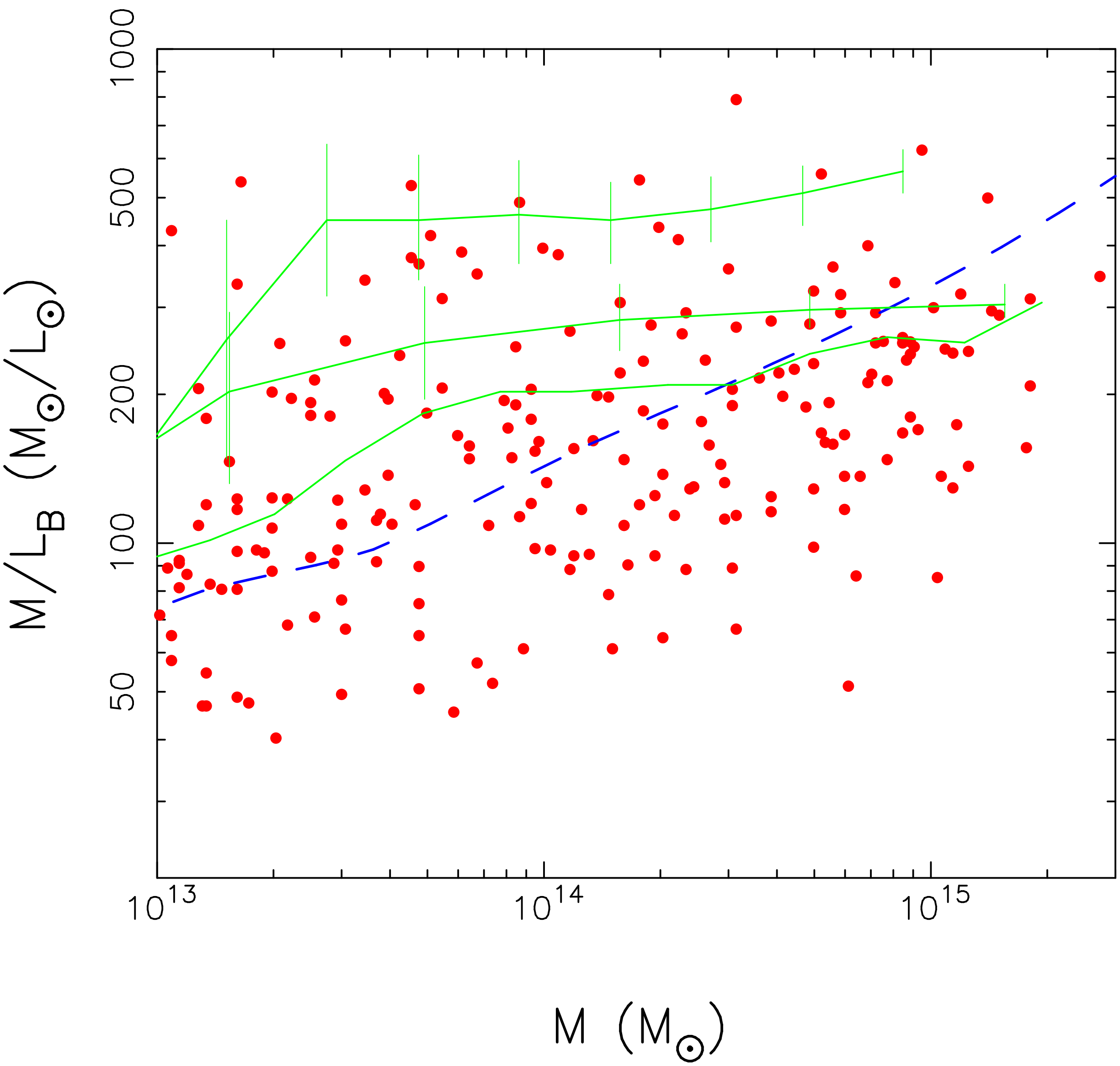

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M/L_B $(M_\odot/L_\odot)$
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